How Dr. Einstein Has Modified Our Ideas of Nature

The Theory of Relativity Explained by Dr. Russell, Professor of Astronomy at Princeton

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IT IS probably a long time since there has been any occasion on which a matter so definitely belonging to pure science as the "theory of Einstein" has excited so much popular interest.

Although the statements in the newspapers concerning "the overthrow of Newton's laws" and similar "scare heads" have gone beyond the more sober statements of scientific authorities, it is nevertheless true that the theory of relativity, of which the recent work of Einstein forms an extension, has modified our conceptions of nature in a very remarkable fashion.

Einstein's reported statement that there were not more than twelve men in the world who could read and fully understand his book was probably quite within the facts. But the elementary ideas on which the theory of relativity is based do not involve any difficult mathematics, and the only obstacle to grasping or holding them is their remarkable novelty. We can understand them easily enough, or at least understand what they are about, if only we begin at the beginning.

Our Complicated Movements

It probably has not occurred to all of you that while I was speaking the last sentence we traveled several hundred miles. Yet, of course, we did. If we had not, the earth would have left us behind it somewhere in empty space.

In fact, we are undergoing a very complicated series of motions, carried around with the rotating earth and swinging along much more rapidly and in a much vaster curve with its orbital motion.

But of this fact we are blissfully unconscious. Why? Because the motion is perfectly smooth, without jar or shock, and in particular because not merely we ourselves but all the objects that constitute our environment are moving together.

So we come to one of the main conceptions of the theory of relativity, the moving frame of reference.

We ordinarily refer our measurements and indeed our notions of distance and of motion to some frame, what the mathematician would call some system of coördinates, which, so to speak, is "tied" to some definite objects—ordinarily to that portion of the earth's surface on which we may have set ourselves or over which we may be traveling at the moment.

Though we and all our well informed ancestors for two centuries have known very well that this frame of reference is not at rest but is in rapid and intricate motion, we are, nevertheless, still accustomed to referring our motions to this moving frame and saying that a thing has not budged when its position with respect to the ground has not altered.

A Working Basis

And in doing this we not only follow the promptings of common sense but find a practical and working basis for the scientific description of almost all terrestrial affairs.

But the moment we begin to look off the earth into space things are different. It then becomes obvious that the earth is not at rest but moving, both on its own axis and about the sun.

I say "obvious"; but it is worth remembering that these facts—at present so familiar even to the man in the street—aroused, when their truth was first advocated, the most violent disbelief and agitation, and that it took a century or more of controversy to displace the old, innate belief in the fixity of the earth, that is, of our frame of reference, and substitute the belief that it was in motion.

So far as our solar system goes we may comfortably treat the sun as being at rest and attach our frame of reference to it. But when we come to look still further afield at the stars we find them in motion and later detect a drifting tendency among them which indicates beyond question that our sun itself is moving.

Sun Moving, Too

So next we hitch our frame of reference onto a sort of average position of all the stars visible to the naked eye, and find that with respect to this new frame of reference the sun and planets are moving at the rate of about twelve miles a second in a definitely known direction.

We were content with this until within the last decade, when observations upon the nebulæ, which we know now to be enormously further off than the naked eye stars, revealed extremely rapid motions.

If we try now to hang a frame of reference, so to speak, to the average of these nebulæ, it begins to look as if our solar system was moving, compared with this, at a speed of something like four hundred miles a second, which motion, of course, the system of stars visible to the naked eye must substantially share.

But now, which of all these systems is really moving?

Are the stars at rest and the nebulæ moving, or are the nebulæ at rest and the stars moving, or are they both moving past each other in different directions, and is there anything at rest? Can we really find anything anywhere in the material universe upon which we can really set the feet of our imagination and say "J'y suis, j'y reste," with the conviction that we are at last upon the firm rock of the absolutely motionless?

DR. ALBERT EINSTEIN, a Swiss Jew, whose promulgation of the theory of relativity has modified our ideas of nature. Dr. Einstein's discoveries are considered the most important since Newton's discovery of gravitation

Birth of the Theory

It is from a search for an answer to this question that the theory of relativity grew.

The first great contribution was made by Newton. An immediate consequence of his fundamental principles of physical science is that if we have a number of objects moving together in space, which we may call a system, acting upon one another in any fashion, however complicated, but free from outside influence, then the relative motions of the bodies in that system will not depend at all upon the rate at which the system as a whole is moving through space, or the direction of its motion, but only upon the mutual interaction of its parts.

Simple uniform motion in a straight line, what we technically call a "motion of translation," does not influence the things that happen in the system at all, even to the minutest degree. Therefore, an observer within the system cannot hope to detect it unless he has something outside to observe. It is on account of this great dynamic principle that we are unconscious of the motion of the earth about the sun.

In our proposed search, then, for "absolute motion" we must use some other means, and our most efficient tools are likely to be the waves of light. We know that light spreads out from any hot body into space in all directions and at the great speed of 186,000 miles a second.

Ether as a Basis

Despite this enormous velocity, something real actually travels outward, because it carries with it energy which is, to the modern physicist, one of the most fundamental of all realities.

This energy may still be perceptible to our eyes or apparatus when reaching us from the stars after a journey which has consumed many thousands of years.

We know, too, that this energy, while it is on its way, travels in a manner strikingly similar to the propagation of waves, so much so that we feel justified in describing light as consisting of waves of definite lengths and properties.

Now, how does this energy travel through apparently empty space with these singular wave properties? The natural answer, almost the intuitive answer, is to say that it travels through a medium, and so we invent the "ether," simply as the medium which carries the light.

But if there is such a medium in space—and light travels through it in every direction at the same speed—it would seem as if here, at last, in this undisturbed ether we had our frame of reference which we could use as our basis for the measurement of all other motions.

The Proof

If this be true, we can detect whether this world of ours is moving through the ether or not by sending light signals through equal distances in different directions and seeing whether they come back to us at the same interval of time.

To see how the thing works, let us suppose first that we have an observer at rest with respect to the ether and surrounded by a circle of mirrors set in various directions from him, but all at a distance of 186,000 miles.

If he then produces a flash of light at his own position this light will travel out and in one second will reach all the mirrors simultaneously, will be reflected at each, and at the end of another second will come back to him simultaneously from all the mirrors. (If this hypothetical apparatus appears to you inconveniently large, you can just as well imagine one a million times smaller, which would make the radius of the circle about a thousand feet, and count your time in millionths of a second instead of whole seconds.)

So far so good. But now suppose that the observer and his whole circle of mirrors, big or small, are not at rest, but are all moving together uniformly at a speed of half the velocity of light.

Now, let the observer send out a light signal and wait for its reflection from that mirror which is directly on the line of his track and in the direction toward which he is moving.

A Stern Chase

The light traveling out toward this mirror would itself move 186,000 miles a second, but would have a "stern chase," since the mirror is receding half as fast as it is traveling, and it is easy to see that it would take two whole seconds to reach the mirror.

On the return journey the observer will be advancing to meet it with half the speed of light, and this part of the process will take only two-thirds of a second. The elapsed time for the round trip of the light will be two and two-thirds seconds, considerably longer than if the observer was at rest.

Consider next a ray of light which gets reflected in the mirror, whose direction from the observer is at right angles to the first.

It will not have the long stern chase which the first ray has, but nevertheless it will lose something, because in order to reach the moving mirror it will have to travel "on the bias," so to speak, through space, so that it will reach not the point where the mirror was when the light started, but the point where it will be when it gets there, and something quite similar will happen on the return journey.

When this is calculated it is found that the round trip will in this case take about two and one-third seconds. (The exact amount involves calculating a square root that we need not bother with here.)

The important point is that in this case, where the observer and mirrors are moving through the ether, the ray of light which has traveled up and down the direction of motion will take a longer time for the round trip than the ray which has traveled crosswise to the motion over a path of exactly the same length.

Could Detect Motion

We should, therefore, in this way be able to detect motion of our own system through the ether, and if our measurements were sufficiently accurate, determine its direction and rate.

This was attempted in the famous Michelson-Morley experiment. The distance of the round trip was in this case only a few feet, and the difference in time over the two paths only something like a millionth part of one-billionth of a second.

But this minute interval could be measured by splitting a ray of light into two parts by letting part of it be reflected sidewise from a transparent mirror and the rest go through, and reuniting the parts after their trip.

If one had gained on the other by even a fraction of the time of vibration of a single light wave the fact could be detected, and the waves which we ordinarily call light vibrate at the rate of about six hundred thousand billion a second.

Michelson and Morley tried their experiment and in place of the easily measurable result which they anticipated they got nothing. The light waves came back over the two paths in exactly the same interval of time.

They tried it again and again at different times of the year, when the earth was moving in different directions around the sun, so that even though the earth might have been at rest in space on some one of these days, it certainly was not at rest on all of them. But they always met the same negative result.

Experiments Failed

Other optical experiments of a more intricate nature and even greater delicacy were attempted with the same object of detecting the motion of the earth through the ether and they all failed.

After it became clear that the trouble was not in the apparatus or the experiment, it was evidently necessary to account for the absence of the predicted effect.

After various minor hypotheses had been tried, Einstein started in with the bold assumption that these experiments had unveiled a new law of nature, viz., that the universe was so constructed that it was not possible by any physical experiment, optical or otherwise, to detect the existence of absolute, uniform, straight-ahead motion, or, indeed, to determine whether the observer's frame of reference was at rest or in such uniform translational motion.

If this is true, it follows that it is only the *relative* motions of material bodies in the universe which we can study at all.

Hence the name of the principle of relativity.

A second principle following naturally from the experiments which led to the first is that the velocity of light in empty space will always come out the same, whether measured by an observer moving with his apparatus in one direction at one rate or by one similarly moving in another direction and at a different rate.

Novel Consequences

This principle sounds harmless enough, but the consequences which follow from it are so different from our old preconceived opinions that they often appear to us grotesque to a degree.

Take one of the simplest ones.

Let us go back to the observer with a ring of mirrors surrounding him, from all of which the reflections of his flash of light reach him at the same instant. If he thinks that he is at rest in space he will say that these mirrors are distributed around a perfect circle, with his own position as center.

Now, suppose he chooses a different frame of reference, in uniform motion compared with his original one. That is, suppose that he thinks that he and the mirrors together are moving uniformly in some particular direction and at a high velocity.

He will now say, "If these mirrors were really on a circle the light would take longer to reach me from those which were in the direction of my path than from those at right angles. Since the light returns simultaneously from all, the mirrors are not arranged on a circle but on an ellipse, which is longer at right angles to the direction of my motion than it is the other way."

If, as in the case previously discussed, he supposes himself to be moving with half the speed of light, he will conclude that the longer diameter of this ellipse is about 15 per cent greater than the shorter diameter. If he estimates his own velocity higher, he will regard it as differing still more from a circle.

The Lorentz Theory

But although the mirrors in this case are not all at equal distances from him, he cannot find this out by measuring the distance with a measuring rod. In fact, if he does so, their distance will all appear to be exactly the same, if the principle of relativity is true. For otherwise, by combining an optical experiment and a direct measurement he would have a method by which he could distinguish between rest and uniform motion; and this is, by the very hypothesis, impossible.

Hence nature must be so constituted that his measuring rod would automatically change in length when turned from a position parallel to his motion to one at right angles to it.

This sounds strange enough, but something of the sort is entirely necessary in order to explain the Michelson-Morley experiment. The assumption that material bodies, when moving through space, contract slightly in the direction of motion was made by Lorentz in order to explain this experiment before the more general theory had been developed. At such speeds as are actually reached by the planets in their orbits the contraction is less than one part in one hundred million, and beyond detection by anything except the most refined investigations.

We have now seen that, according to the principle of relativity, the answer to the question whether two material rods laid on the table at right angles to one another are of the same length or of different lengths depends on whether we choose to think that we and the room in which the apparatus is situated and the rest of the world are at rest in space or are moving in different directions with high uniform speeds.

Measurement of Time

The fact that when the two rods are laid side by side they are obviously exactly equal does not prove that they are the same length when we turn them so that they make an angle with one another.

So much for the measuring of distances and the measuring of the lengths of things.

Now, how about measuring time?

Let us go back to the observer with his mirror and call him A, and suppose that at the mirror there is a second observer whom we will call B, and that both observers have clocks which run with perfect accuracy, and are able to observe the time of anything with the aid of their clocks as precisely as you please.

Now let us suppose that exactly at 12 noon A sends a flash of light out toward B. B perceives it at the instant when it is reflected by his mirror and notes the time as exactly 1 second past 12 o'clock. A observes the reflected signal at 2 seconds past 12 o'clock.

Repetitions of this signal on successive days give exactly the same result. A and B will conclude that the distance between them does not change, since it always takes light the same time to make the round trip, and that their clocks are running at the same rate.

Now suppose that A and B regard themselves as at rest. They will then agree that the distance between them is 186,000 miles, since it takes light one second to go each way, and they will also agree that their clocks are not merely running at the same rate but are exactly synchronized, because the light must have reached B just one second after it left A.

But now suppose that A and B agree in the belief that they are moving through space with half the speed of light, so that they are following the same track with B preceding A.

Going and Coming

Using the same principle of the stern chase of which we have spoken before, they will now figure out their distance apart as not 186,000 miles, but just three-fourths as much, or 139,500 miles, and also that the light in going outward over this distance from A to B on the stern chase took one and a half seconds, whereas in coming back it occupied only one second.

This change in the direction amounts to exactly the same thing which we described a few moments ago; but there will be a second interesting change with respect to their measurement of time. For since they now believe that the light took one and a half seconds to go out, the time when it reached B was one and a half seconds past noon by A's clock and only one second past noon by B's clock.

Hence they will agree that B's clock is half a second fast.

On the other hand, it is easy to see that, if they had supposed themselves to be going along the same line, and at the same rate of speed, but in the opposite direction, they would have concluded that B's clock was half a second slow.

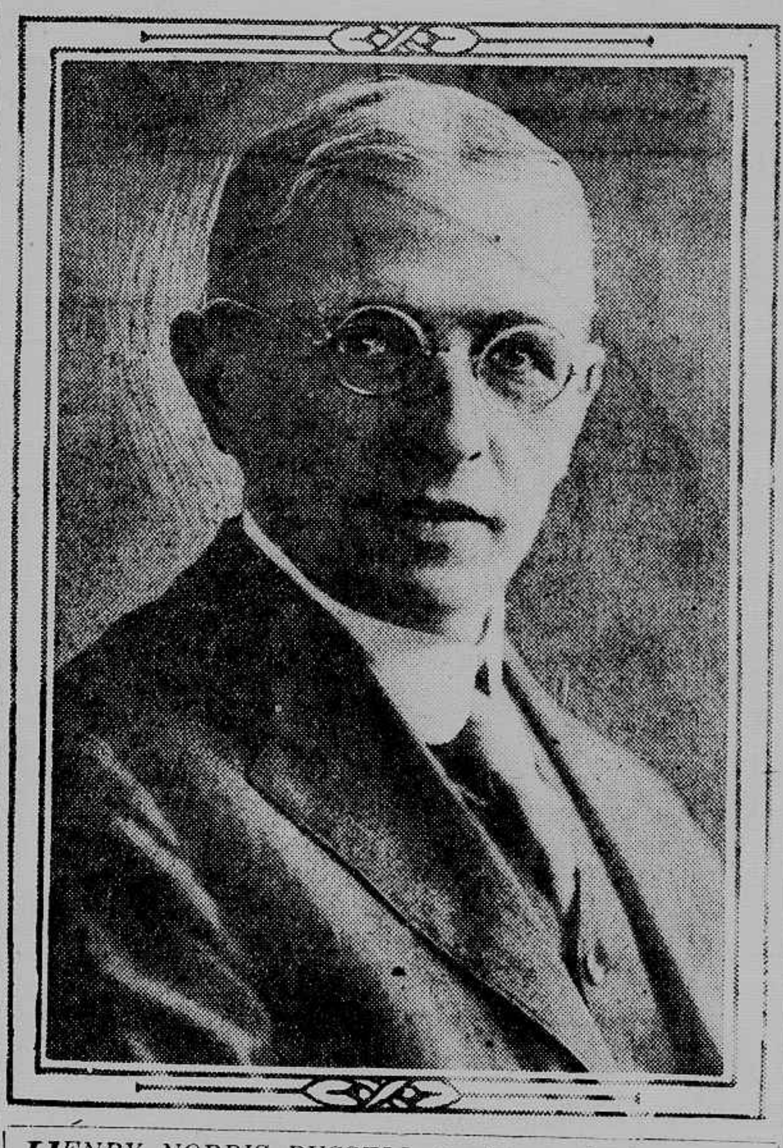
We reach, therefore, the still more picturesque conclusion that the question whether or not two events which take place at different points of space are simultaneous or occur at different times cannot be answered until we have defined the uniformly moving frame of reference with respect to which we are to make our measurements and reasoning.

With the distance that we have assumed, the difference between the two clocks would be only a fraction of a second, even if the assumed speed was very great. But if we had taken a distance such as that between the remoter stars, whose light takes thousands of years to travel, then, according to our choice of a frame of reference, we might have been led to the conclusion that A's clock was either in agreement with B's or fast or slow by several centuries.

To the General Public It Is Startling to Learn That Light Does Not Travel in a Straight Line

Once again, the possible difference between the results of different assumptions are immeasurably small for such observations as could be made upon our tiny and slowly moving earth. But for such distances as separate the stars and for greater assumed speeds they may become extremely large.

I might go on to describe what happens if we imagine two observers, A and B, receding from one another with half the speed of light and exchanging signals by a reflection back and forward from mirrors carried by both. As I have not a blackboard, I will spare you the details, which are not hard for any one to work out who takes a pencil and piece of paper.



HENRY NORRIS RUSSELL, professor of astronomy at Princeton University, who explains the much discussed theory of relativity for the benefit of the layman

Space and Time

I will simply state the result that, given a certain set of definitely observed facts upon which both observers are entirely and perfectly agreed, it is possible that A, if he considers himself at rest, will say that B is receding from him with half the velocity of light and carrying a clock which is running at exactly the same rate as his own, while B, who naturally may prefer to think of himself as at rest, and the other fellow moving, will believe that A is receding from him with half the speed of light, but will insist that his clock and A's clock are not keeping together, but are running at different rates.

The root of this extraordinary discrepancy between their opinions will lie in the fact that they divide up the round-trip time interval for the reflected light waves in different manners on account of their different assumptions as to whether the reflecting mirrors are at rest or being chased by the light, thereby introducing a difference into their methods of comparing one another's clocks, which continually increases as the distance between them increases and the round-trip time for the light with it.

I have certainly gone far enough now to show you how we are led, if we stick to these apparently simple and harmless principles of relativity, into the most extraordinary conclusions with respect to space and time.

As some one has well put it, "whenness" and "whereness" are all mixed up together. You can't say just when a thing happened without saying where it happened, and also with respect to what frame of reference you define both when and where.

All these spectacular changes, however, reach perceptible amounts only for objects which are moving with at least a moderate fraction of the velocity of light; and the actual motion of the planets is so much slower than this that no perceptible differences will be introduced by our choosing frames of reference which are attached to the earth, the sun, the planets or the stars.

His Hypothesis Confirmed

Not content with these remarkable results, Einstein proceeded a few years ago to generalize his theory further, in imagining another type of question which did not come within even the wide view of the older relativity theory.

To make this idea clear let us imagine two observers, each with his measuring instruments, means of subsistence, etc., in a large and perfectly impervious box which forms his "closed system."

The first observer, with his box and its contents, alone in space, very remote from all gravitating bodies and entirely at rest.

The second observer, with his box and its contents, is, it may be imagined, near the earth or the sun or some star and falling freely under the influence of its gravitation.

To be more precise, we imagine him in what is called a "uniform gravitational field," where the gravitational force is exerted on all objects in exactly the same direction and is not converging toward the center of the attracting body, where it is always of exactly the same amount and there is nothing to interfere with an indefinitely long fall.

This second box and its contents, including the observer, will then fall under the gravitational force—that is, get up an ever-increasing speed, but at exactly the same rate, so that there will be no tendency for their relative positions to be altered.

According to Newton's principle, this will make not the slightest difference in motions of the physical objects comprising the system or their attractions on one another, so that no dynamical experiment can distinguish between the condition of the freely falling observer in the second box and the observer at rest in the first.

But once more the question arises: What could be done by an optical experiment?

According to the beliefs which have been held from the time of Maxwell, who first developed the electro-magnetic theory of light, until the present, it has generally been believed that gravitation, however powerful, has no effect whatever upon light, and the light would therefore travel in a straight line through a field of gravitational attraction exactly as it would through empty space.

How Light Travels

Einstein, on the other hand, assumed, just for the fun of seeing what would come of it, that the principle of relativity still applied in this case, so that it would be impossible to distinguish between the conditions of the observers in the two boxes by any optical experiment.

It can easily be seen that it follows from this new generalized relativity of Einstein that light cannot travel in a straight line in a gravitational field.

Imagine that the first observer sets up three slits, all in a straight line, at considerable distances apart. A ray of light which passes through the first and second will obviously pass exactly through the third.

Suppose the observer in the freely falling system attempts the same experiment, placing the line of his three slits at right angles to the direction in which he is falling and having them equally spaced.

The ray of light which has passed the first slit must, in order to go through the second, move not toward the point where that slit was when it emerged from the first, but toward the point where the second slit will be when the light reaches it.

It will, therefore, be moving not at right angles to the direction in which the system is falling, but at a slant, so that during the interval in which it has traveled laterally from the first slit to the second it will have moved downward by a certain fixed amount, namely, by the amount through which the system fell in that interval.

In moving from the second to the third slit, the light will occupy the same interval of time, and, if it moves in a straight line, will go downward by the same amount as before.

But since the system is falling ever faster and faster, it will during this time interval have dropped further than it did in the preceding time interval and carried the third slit with it.

Hence, the ray of light will strike above the third slit and fail to go through it, provided it is moving in a straight line in space.

But on Einstein's assumption it must go through the third slit, since the two conditions are indistinguishable.

Path Not Straight

In consequence, the path of the light in space must be curved and not straight when gravitation is present, and the ray of light must bend downward, that is, in the direction of the gravitational force.

This deduction from Einstein's new principle may thus be reached in a very simple fashion, but the further following out of the prin-

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Proof of the Einstein Theory

IT WAS approximately fifteen years ago when Dr. Albert Einstein first made known his "theory of relativity."

The present revival of interest in the theory is due to the remarkable confirmation which it received in the reports of observation made during the sun's eclipse last May to determine whether rays of light passing close to the sun are deflected from their course.

The actual deflection of the rays, it was discovered by the astronomers, was exactly what had been predicted theoretically by Einstein many years before.

Observation then proved that the rays of fixed stars, having to pass close to the sun to reach the earth, were deflected by the exact amount demanded by Einstein's formula. The deflection was also in the direction predicted by him.

Asked one time to express the difference between his conception and the law of gravitation in terms understandable to the layman, Dr. Einstein stated:

"Please imagine the earth removed, and in its place suspended a box as big as a room, or a whole house, and inside a man naturally floating in the center, there being no force whatever pulling him.

"Imagine, further, this box being, by a rope or other contrivance, suddenly jerked to one side, which is scientifically termed 'accelerated motion.' The person would then naturally reach bottom on the opposite side.

"The result would consequently be the same as if he obeyed Newton's Law of Gravitation, while, in fact, there is no gravitation exerted whatever, which proves that 'accelerated motion' will in every case produce the same effects as gravitation.

"I have applied this new idea to every kind of 'accelerated motion,' and have thus developed mathematical formulas which I am convinced give more precise results than those based on Newton's theory. Newton's formulas, however, are such close approximations that it was difficult to find by observation any obvious disagreement with experiments."